US009080316B2

(12) **United States Patent**
Colwell et al.

(10) **Patent No.: US 9,080,316 B2**
(45) **Date of Patent: *Jul. 14, 2015**

(54) **CONTROLLING A DIGGING OPERATION OF AN INDUSTRIAL MACHINE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **14/224,218**

(22) Filed: **Mar. 25, 2014**

(65) **Prior Publication Data**

US 2014/0207345 A1 Jul. 24, 2014

Related U.S. Application Data

(63) Continuation of application No. 13/959,921, filed on Aug. 6, 2013, now Pat. No. 8,682,542, which is a continuation of application No. 13/222,939, filed on Aug. 31, 2011, now Pat. No. 8,504,255.

(60) Provisional application No. 61/480,603, filed on Apr. 29, 2011.

(51) **Int. Cl.**
E02F 3/43 (2006.01)
E02F 3/46 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***E02F 3/431*** (2013.01); ***E02F 3/304*** (2013.01); ***E02F 3/308*** (2013.01); ***E02F 3/43*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC E02F 3/46; E02F 9/2029; E02F 9/265; E02F 3/308; E02F 9/2025; E02F 3/435; E02F 4/431; E02F 3/304; E02F 3/43
USPC 701/50, 49; 414/685, 694, 699, 718, 414/726; 37/443, 394–398, 348, 384; 702/41, 44, 174
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,207,339 A 9/1965 Nelsin
3,518,444 A 6/1970 Barber
(Continued)

FOREIGN PATENT DOCUMENTS

AU	5826586	1/1987
JP	6026067	2/1994
WO	2009152561	12/2009

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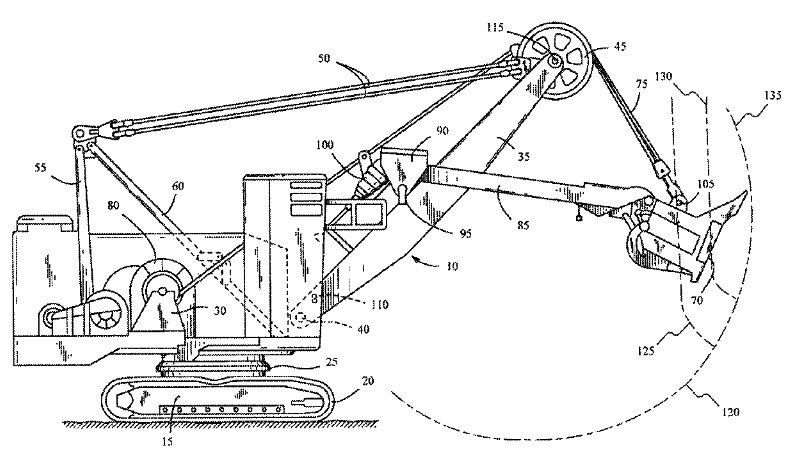
(57) **ABSTRACT**

Systems, methods, devices, and computer readable media for controlling the operation of an industrial machine including one or more components. A method of controlling the industrial machine includes determining a position of at least one of the one or more components of the industrial machine during a digging operation, determining a hoist bail pull setting based on the position of the at least one of the one or more components and a relationship between component position and hoist bail pull, and setting a level of hoist bail pull to the hoist bail pull setting. The level of hoist bail pull early in the digging operation is greater than the level of hoist bail pull later in the digging operation.

37 Claims, 8 Drawing Sheets



(51) **Int. Cl.**
E02F 9/20 (2006.01)
E02F 9/26 (2006.01)
E02F 3/30 (2006.01)

(52) **U.S. Cl.**
CPC . ***E02F 3/435*** (2013.01); ***E02F 3/46*** (2013.01); ***E02F 9/2025*** (2013.01); ***E02F 9/2029*** (2013.01); ***E02F 9/265*** (2013.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,586,184	A	6/1971	Pesavento et al.	
3,934,126	A	1/1976	Zalesov et al.	
4,308,489	A	12/1981	Bergmann	
4,358,719	A	11/1982	Currier et al.	
5,363,304	A	11/1994	Awano et al.	
5,408,767	A	4/1995	Hazama et al.	
5,461,803	A	10/1995	Rocke	
6,025,686	A	2/2000	Wickert et al.	
6,225,574	B1	5/2001	Chang et al.	
6,466,850	B1	10/2002	Hilgart	
7,152,349	B1	12/2006	Rowlands	
7,472,009	B2	12/2008	Baldwin	
RE40,869	E	8/2009	Leslie et al.	
7,689,394	B2	3/2010	Furem et al.	
7,734,397	B2	6/2010	Peterson et al.	
7,832,126	B2	11/2010	Koellner et al.	
8,504,255	B2	8/2013	Colwell et al.	
2006/0124323	A1	6/2006	Glover et al.	
2007/0006492	A1	1/2007	Rowlands	
2007/0240341	A1	10/2007	Hyde	
2007/0266601	A1*	11/2007	Claxton	37/396
2009/0187527	A1*	7/2009	Mcaree et al.	706/52
2011/0029279	A1	2/2011	McAree et al.	
2011/0088290	A1	4/2011	Rowlands	

* cited by examiner

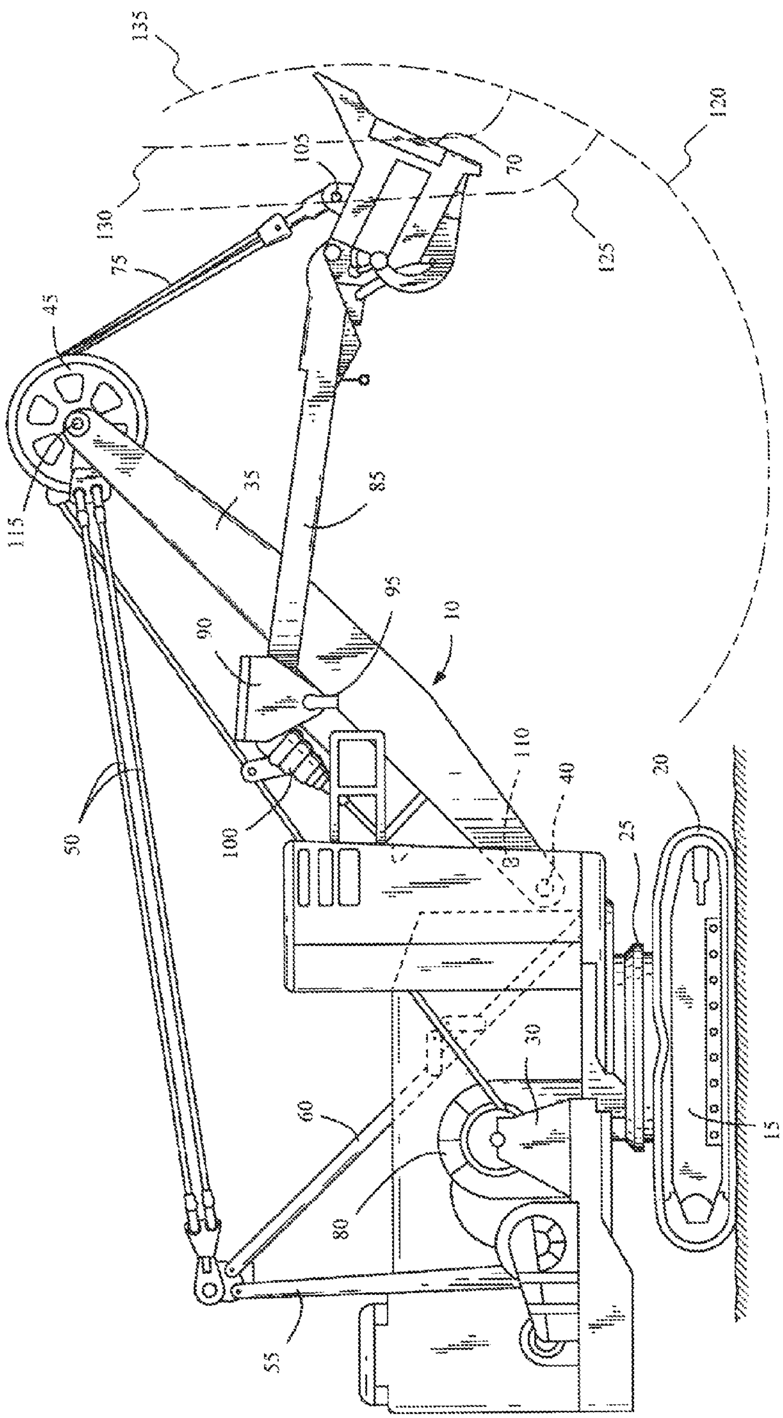
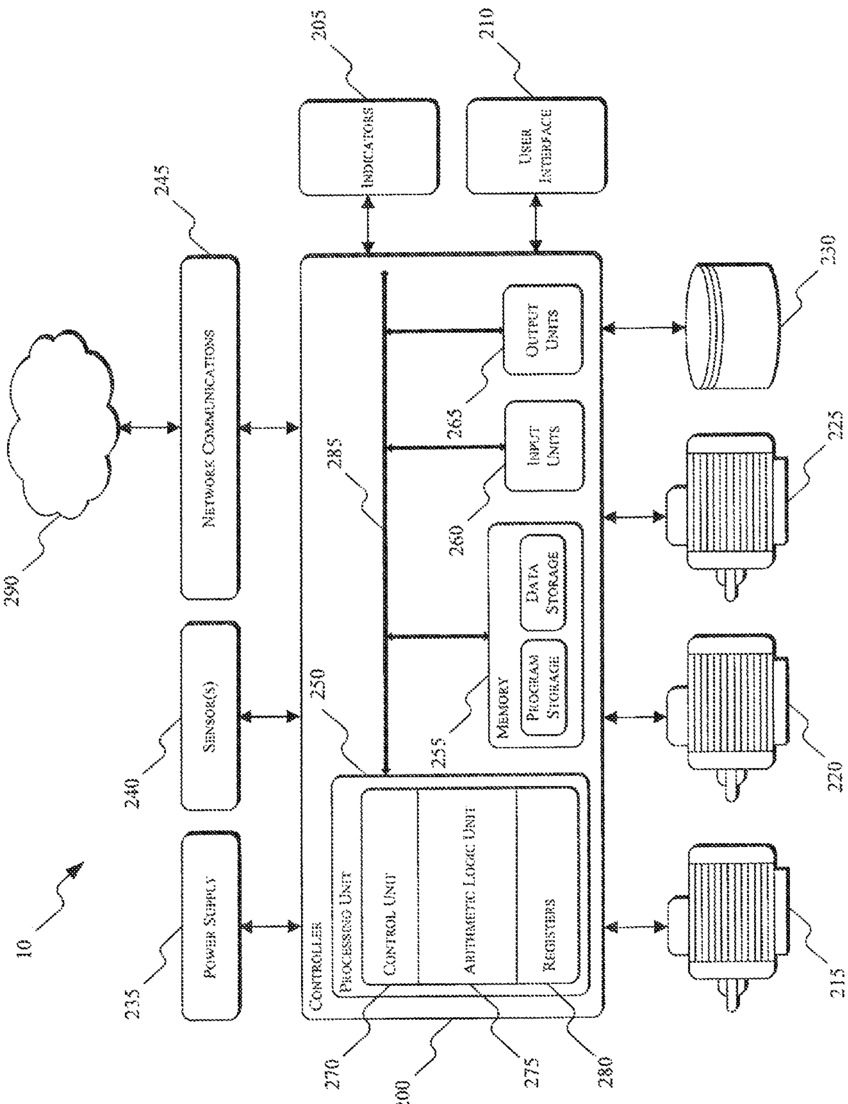

135
120
105
70
130
125
75
45
85
35
115
95
10
90
110
40
20
25
50
100
30
15
60
80
55

FIG. 1

FIG. 2


10
Power Supply
Sensor(s)
Network Communications
Indicators
User Interface
Controller
Processing Unit
Control Unit
Arithmetic Logic Unit
Registers
Memory
Program Storage
Data Storage
Input Units
Output Units
200
205
210
215
220
225
230
235
240
245
250
255
260
265
270
275
280
285
290

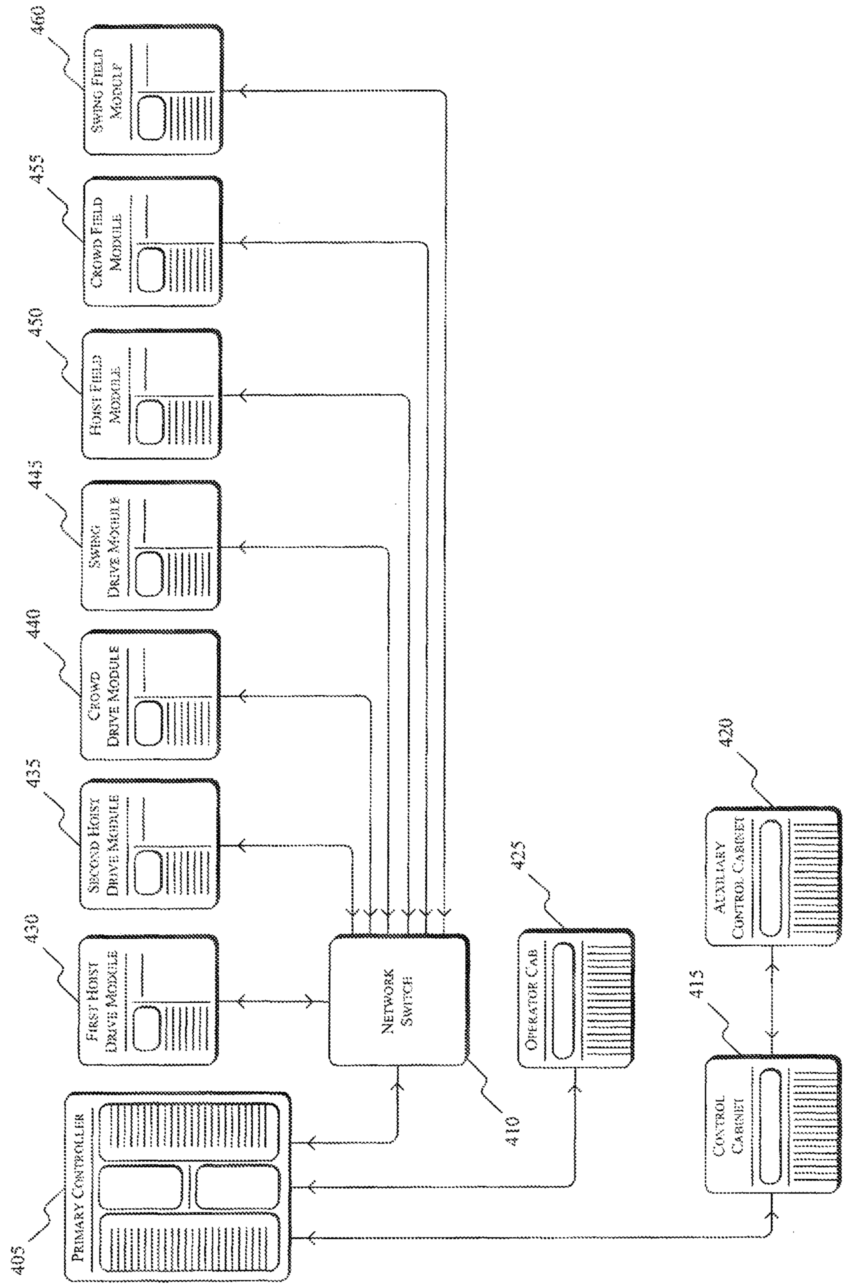
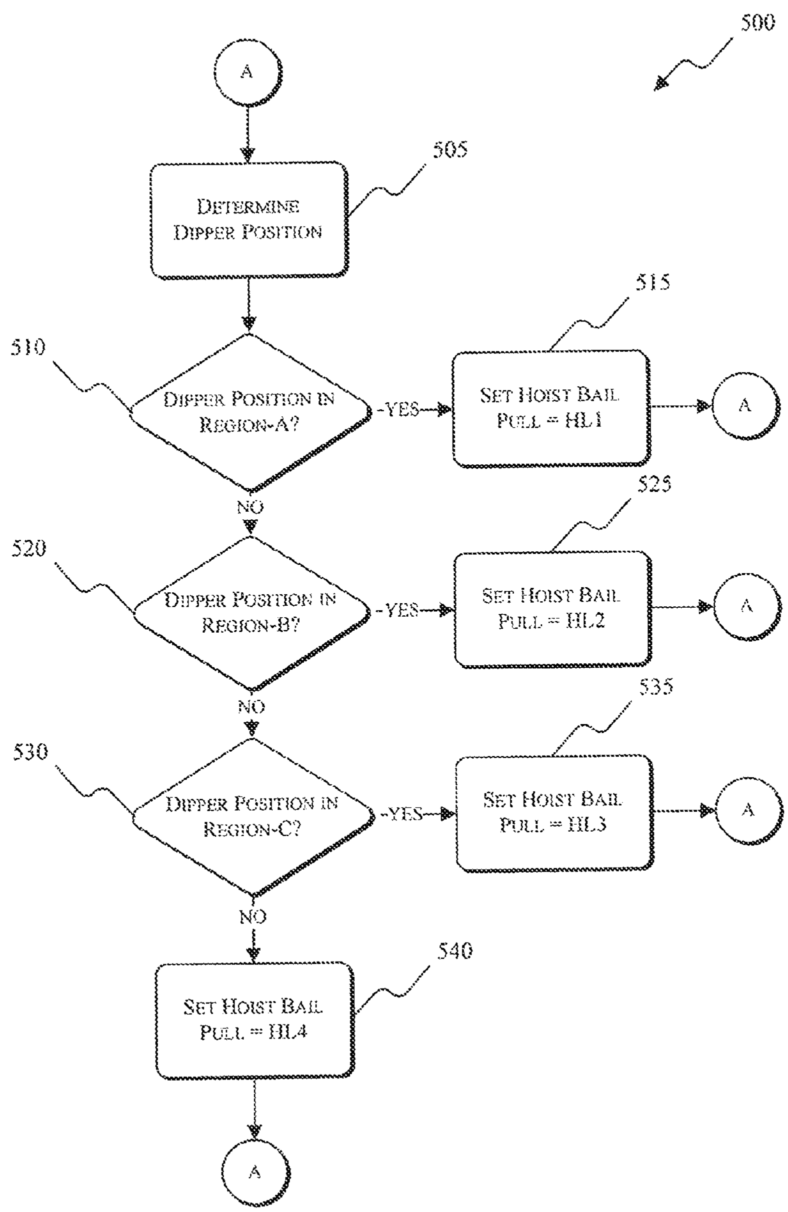

400
Primary Controller
405
Network Switch
410
Control Cabinet
415
Auxiliary Control Cabinet
420
Operator Cab
425
First Hoist Drive Module
430
Second Hoist Drive Module
435
Crowd Drive Module
440
Swing Drive Module
445
Hoist Field Module
450
Crowd Field Module
455
Swing Field Module
460

FIG. 3

FIG. 4


500
A
505
DETERMINE DIPPER POSITION
510
DIPPER POSITION IN REGION-A?
YES
515
SET HOIST BAIL PULL = HL1
A
NO
520
DIPPER POSITION IN REGION-B?
YES
525
SET HOIST BAIL PULL = HL2
A
NO
530
DIPPER POSITION IN REGION-C?
YES
535
SET HOIST BAIL PULL = HL3
A
NO
540
SET HOIST BAIL PULL = HL4
A

600

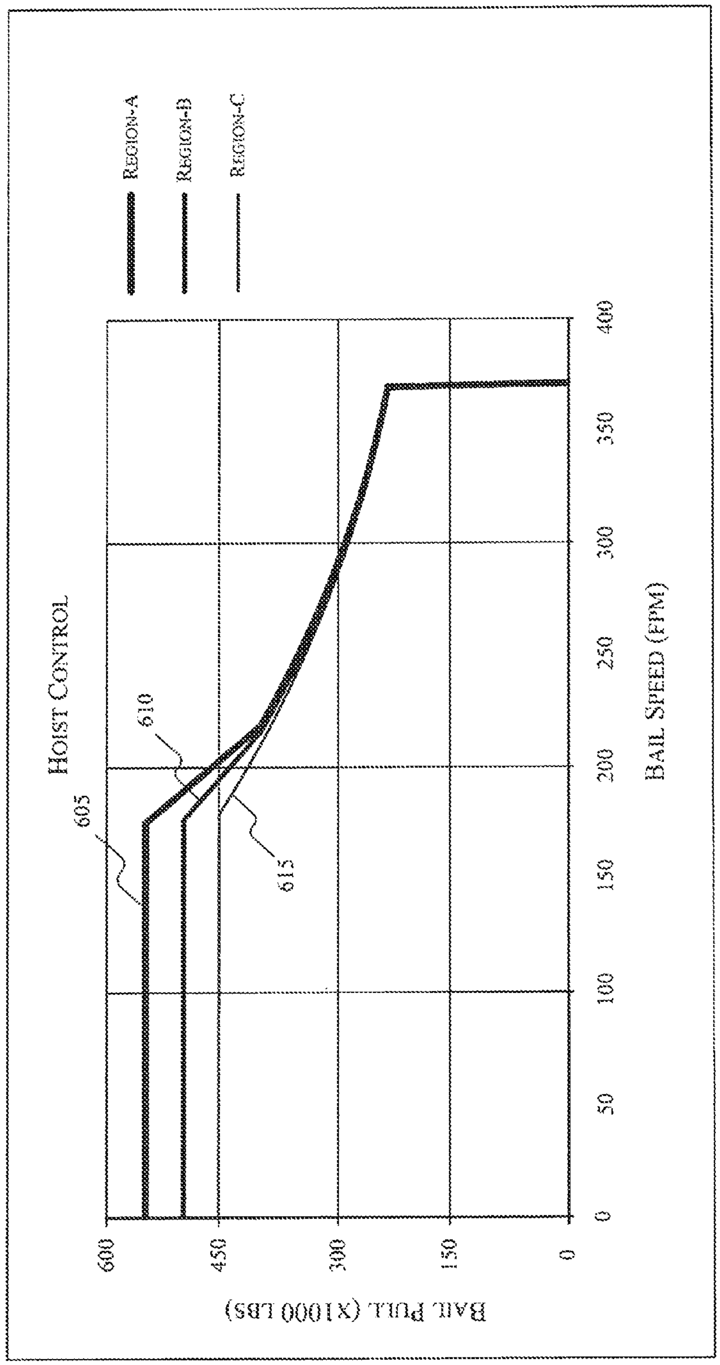

HOIST CONTROL
REGION-A
REGION-B
REGION-C
605
610
615
BAIL PULL (X1000 LBS)
BAIL SPEED (FPM)
600
450
300
150
0
0
50
100
150
200
250
300
350
400

FIG. 5

600

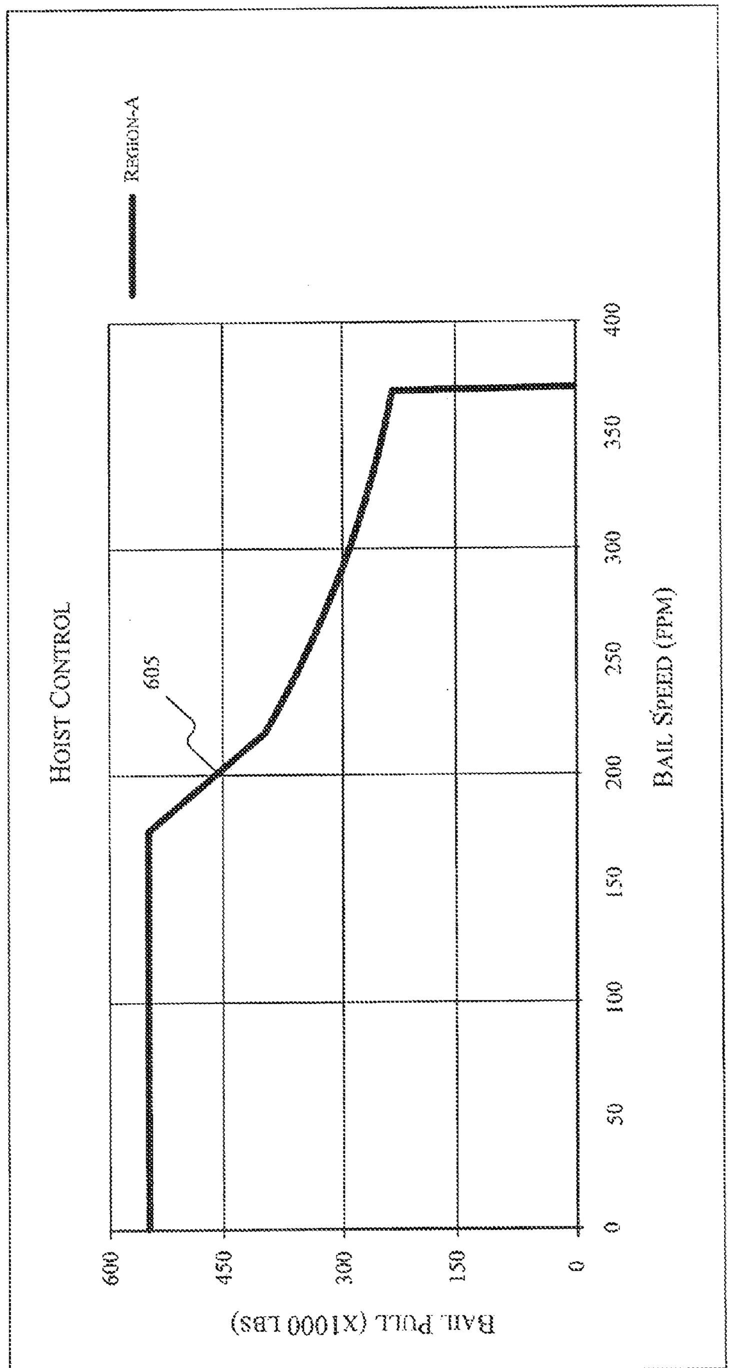

Hoist Control
Region-A
605
Bail Pull (X1000 LBS)
600
450
300
150
0
Bail Speed (FPM)
0
50
100
150
200
250
300
350
400

FIG. 6

600

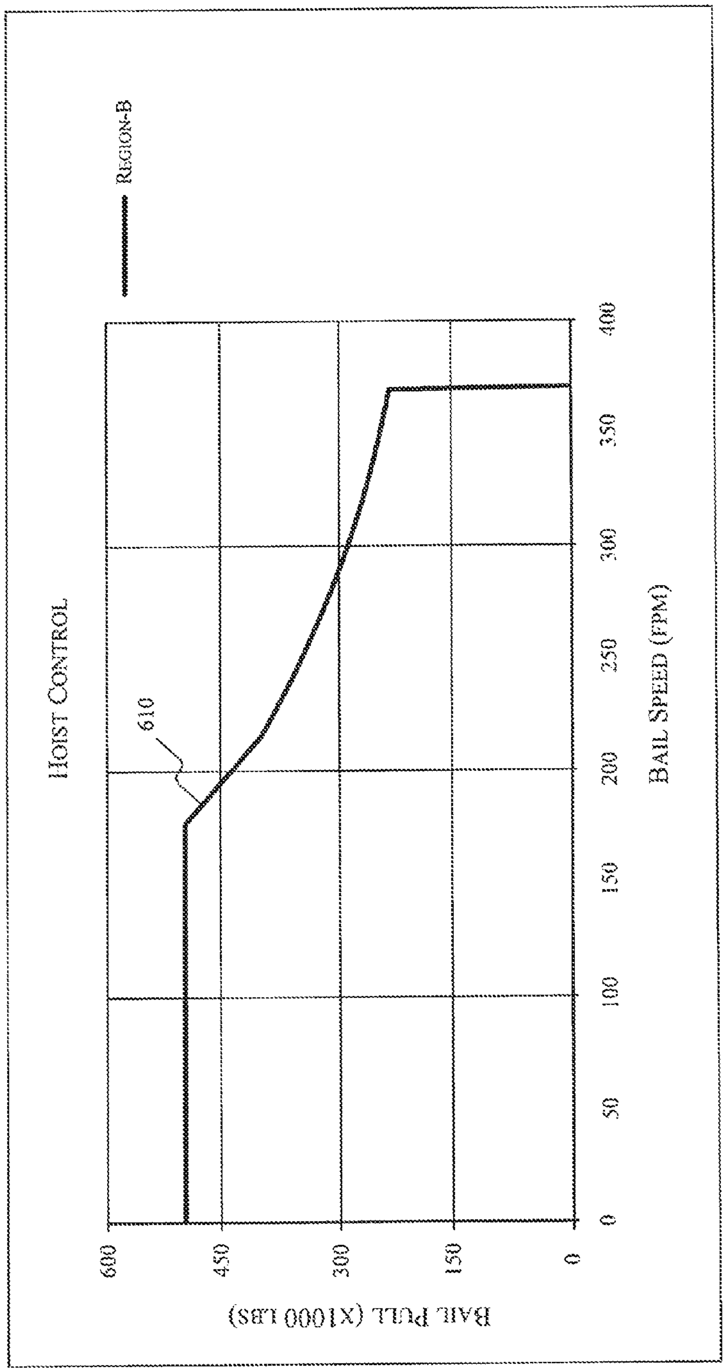
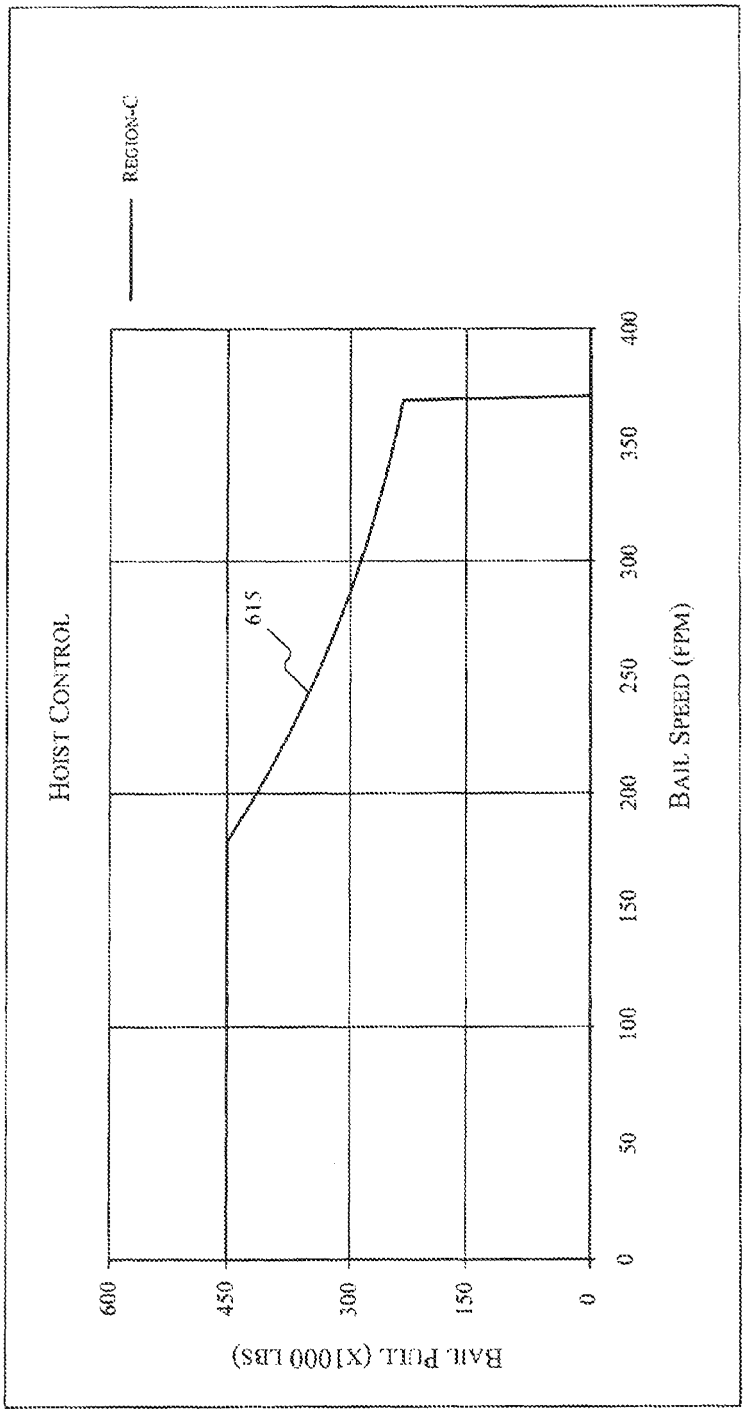

HOIST CONTROL
REGION-B
610
BAIL PULL (X1000 LBS)
600
450
300
150
0
BAIL SPEED (FPM)
0
50
100
150
200
250
300
350
400

FIG. 7

600



HOIST CONTROL
REGION-C
615
BAIL PULL (X1000 LBS)
600
450
300
150
0
BAIL SPEED (FPM)
0
50
100
150
200
250
300
350
400

FIG. 8

CONTROLLING A DIGGING OPERATION OF AN INDUSTRIAL MACHINE

RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 13/959,921, filed Aug. 6, 2013, now U.S. Pat. No. 8,682,542, which is a continuation of U.S. patent application Ser. No. 13/222,939, filed Aug. 31, 2011, now U.S. Pat. No. 8,504,255, which claims the benefit of U.S. Provisional Patent Application No. 61/480,603, filed Apr. 29, 2011, the entire contents of all of which are incorporated herein by reference.

BACKGROUND

This invention relates to controlling a digging operation of an industrial machine, such as an electric rope or power shovel.

SUMMARY

Industrial machines, such as electric rope or power shovels, draglines, etc., are used to execute digging operations to remove material from, for example, a bank of a mine. In difficult mining conditions, the degree to which the industrial machine is tipped in the forward direction impacts the structural fatigue that the industrial machine experiences. Limiting the maximum forward tipping moments and CG excursion of the industrial machine can thus increase the operational life of the industrial machine.

As such, the invention provides for the control of an industrial machine such that the hoisting force or hoist bail pull used during a digging operation is controlled to prevent increased or excessive forward tipping of the industrial machine. This is accomplished while increasing the productivity of the industrial machine by dynamically increasing the level of hoist bail pull low in a digging envelope of the digging operation. As the industrial machine continues through the digging operation and about the digging envelope, the controller gradually decreases the level of hoist bail pull from a maximum level to a lower or standard operational value. The level of hoist bail pull is reduced such that, late in the digging operation, the level of hoist bail pull has reached the standard operational value. Digging cycle time is correspondingly decreased by increasing hoist bail pull, payload low in the digging operation is increased, and the structural fatigue on the industrial machine is maintained at or below the level of an industrial machine without increased hoist bail pull.

In one embodiment, the invention provides a method of controlling a digging operation of an industrial machine. The industrial machine includes a dipper and a hoist motor drive or drives. The method includes determining a first position of the dipper with respect to a digging envelope, determining a first hoist bail pull setting based on the first position of the dipper and a relationship between dipper position and hoist bail pull, and setting a first level of hoist bail pull for the hoist motor drive to the first hoist bail pull setting. The method also includes determining a second position of the dipper with respect to the digging envelope, determining a second hoist bail pull setting based on the second position of the dipper and the relationship between dipper position and hoist bail pull, and setting a second level of hoist bail pull for the hoist motor drive to the second hoist bail pull setting. The first position of the dipper corresponds to a lower position in the digging

envelope than the second position of the dipper, and the first level of hoist bail pull is greater than the second level of hoist bail pull.

In another embodiment, the invention provides an industrial machine that includes a dipper, a hoist motor drive, and a controller. The dipper is connected to one or more hoist ropes. The hoist motor drive is configured to provide one or more drive signals to a hoist motor, and the hoist motor is operable to apply a force to the one or more hoist ropes as the dipper is moved through a digging operation. The controller is connected to the hoist motor drive and is configured to determine a first position of the dipper associated with the digging operation, determine a first hoist bail pull setting based on a relationship between dipper position and hoist bail pull, and set a first level of hoist bail pull for the hoist motor drive to the first hoist bail pull setting. The controller is also configured to determine a second position of the dipper associated with the digging operation, determine a second hoist bail pull setting based on the relationship between dipper position and hoist bail pull, and set a second level of hoist bail pull for the hoist motor drive to the second hoist bail pull setting. The first position of the dipper corresponds to an earlier position in the digging operation than the second position of the dipper, and the first level of hoist bail pull is greater than the second level of hoist bail pull.

In another embodiment, the invention provides a method of controlling a digging operation of an industrial machine that includes one or more components. The method includes determining a position of at least one of the one or more components of the industrial machine during the digging operation, determining a hoist bail pull setting based on the position of at least one of the one or more components and a relationship between component position and hoist bail pull, and setting a level of hoist bail pull to the hoist bail pull setting. The level of hoist bail pull early in the digging operation is greater than the level of hoist bail pull later in the digging operation.

Other aspects of the invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an industrial machine according to an embodiment of the invention.

FIG. **2** illustrates a controller for an industrial machine according to an embodiment of the invention.

FIG. **3** illustrates a control system for an industrial machine according to an embodiment of the invention.

FIG. **4** illustrates a process for controlling an industrial machine according to an embodiment of the invention.

FIGS. **5-8** are diagrams showing relationships between hoist bail pull and bail speed.

DETAILED DESCRIPTION

Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limited. The use of "including," "comprising" or "having" and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. The terms "mounted," "connected" and "coupled" are used broadly and encompass both direct and indirect mounting, connecting and coupling. Further, "connected" and "coupled" are not restricted to physical or mechanical connections or couplings, and can include electrical connections or couplings, whether direct or indirect. Also, electronic communications and notifications may be performed using any known means including direct connections, wireless connections, etc.

It should be noted that a plurality of hardware and software based devices, as well as a plurality of different structural components may be utilized to implement the invention. Furthermore, and as described in subsequent paragraphs, the specific configurations illustrated in the drawings are intended to exemplify embodiments of the invention and that other alternative configurations are possible. The terms "processor" "central processing unit" and "CPU" are interchangeable unless otherwise stated. Where the terms "processor" or "central processing unit" or "CPU" are used as identifying a unit performing specific functions, it should be understood that, unless otherwise stated, those functions can be carried out by a single processor, or multiple processors arranged in any form, including parallel processors, serial processors, tandem processors or cloud processing/cloud computing configurations.

The invention described herein relates to systems, methods, devices, and computer readable media associated with the dynamic control of a hoisting force or hoist bail pull based on a position of, for example, a dipper, a dipper handle, or another component of an industrial machine. The industrial machine, such as an electric rope shovel or similar mining machine, is operable to execute a digging operation to remove a payload (i.e. material) from a bank. As the industrial machine is digging into the bank, the forces on the industrial machine caused by the extension of the dipper handle and the weight of the payload can produce a tipping moment and center-of-gravity ("CG") excursion on the industrial machine in the forward direction. The magnitude of the CG excursion is dependent, in part, on the applied level of hoist bail pull. In general, the greater the level of hoist bail pull, the greater the CG excursion in the forward direction. As a result of the CG excursion, the industrial machine experiences cyclical structural fatigue and stresses that can adversely affect the operational life of the industrial machine. In order to increase the productivity of the industrial machine without increasing the CG excursion experienced by the industrial machine, a controller of the industrial machine dynamically increases the level of hoist bail pull low in a digging envelope of the digging operation. As the industrial machine continues through the digging operation and about the digging envelope, the controller gradually decreases the level of hoist bail pull from a maximum level to a lower or standard operational value. The level of hoist bail pull is reduced such that, late in the digging operation, the level of hoist bail pull has reached, for example, the standard operational value or less than the standard operational value. Digging cycle time is correspondingly decreased, payload early in the digging operation and low in the digging envelope is increased, and the structural loading of the industrial machine is maintained at or below a level for a similar industrial machine that does not use increased hoist bail pull.

Although the invention described herein can be applied to, performed by, or used in conjunction with a variety of industrial machines (e.g., an electric rope shovel, a dragline, AC machines, DC machines, hydraulic machines, etc.), embodiments of the invention described herein are described with respect to an electric rope or power shovel, such as the power shovel **10** shown in FIG. **1**. The shovel **10** includes a mobile base **15**, drive tracks **20**, a turntable **25**, a machinery deck **30**, a boom **35**, a lower end **40**, a sheave **45**, tension cables **50**, a back stay **55**, a stay structure **60**, a dipper **70**, one or more hoist ropes **75**, a winch drum **80**, dipper arm or handle **85**, a saddle block **90**, a pivot point **95**, a transmission unit **100**, a bail pin **105**, an inclinometer **110**, and a sheave pin **115**. In the illustrated embodiment, the shovel **10** also has a digging envelope **120** associated with a digging operation that is divided into three regions: an inner region **125** ("REGION-A"), a middle region **130** ("REGION-B"), and an outer region ("REGION-C").

The mobile base **15** is supported by the drive tracks **20**. The mobile base **15** supports the turntable **25** and the machinery deck **30**. The turntable **25** is capable of 360-degrees of rotation about the machinery deck **30** relative to the mobile base **15**. The boom **35** is pivotally connected at the lower end **40** to the machinery deck **30**. The boom **35** is held in an upwardly and outwardly extending relation to the deck by the tension cables **50** which are anchored to the back stay **55** of the stay structure **60**. The stay structure **60** is rigidly mounted on the machinery deck **30**, and the sheave **45** is rotatably mounted on the upper end of the boom **35**.

The dipper **70** is suspended from the boom **35** by the hoist rope(s) **75**. The hoist rope **75** is wrapped over the sheave **45** and attached to the dipper **70** at the bail pin **105**. The hoist rope **75** is anchored to the winch drum **80** of the machinery deck **30**. As the winch drum **80** rotates, the hoist rope **75** is paid out to lower the dipper **70** or pulled in to raise the dipper **70**. The dipper handle **85** is also rigidly attached to the dipper **70**. The dipper handle **85** is slidably supported in a saddle block **90**, and the saddle block **90** is pivotally mounted to the boom **35** at the pivot point **95**. The dipper handle **85** includes a rack tooth formation thereon which engages a drive pinion mounted in the saddle block **90**. The drive pinion is driven by an electric motor and transmission unit **100** to extend or retract the dipper arm **85** relative to the saddle block **90**.

An electrical power source is mounted to the machinery deck **30** to provide power to one or more hoist electric motors for driving the winch drum **80**, one or more crowd electric motors for driving the saddle block transmission unit **100**, and one or more swing electric motors for turning the turntable **25**. Each of the crowd, hoist, and swing motors can be driven by its own motor controller or drive in response to control signals from a controller, as described below.

FIG. **2** illustrates a controller **200** associated with the power shovel **10** of FIG. **1**. The controller **200** is electrically and/or communicatively connected to a variety of modules or components of the shovel **10**. For example, the illustrated controller **200** is connected to one or more indicators **205**, a user interface module **210**, one or more hoist motors and hoist motor drives **215**, one or more crowd motors and crowd motor drives **220**, one or more swing motors and swing motor drives **225**, a data store or database **230**, a power supply module **235**, one or more sensors **240**, and a network communications module **245**. The controller **200** includes combinations of hardware and software that are operable to, among other things, control the operation of the power shovel **10**, control the position of the boom **35**, the dipper arm **85**, the dipper **70**, etc., activate the one or more indicators **205** (e.g., a liquid crystal display ["LCD"]), monitor the operation of the shovel **10**, etc. The one or more sensors **240** include, among other things, a loadpin strain gauge, the inclinometer **110**, gantry pins, one or more motor field modules, etc. The loadpin strain gauge includes, for example, a bank of strain gauges positioned in an x-direction (e.g., horizontally) and a bank of strain gauges positioned in a y-direction (e.g., vertically) such that a resultant force on the loadpin can be determined.

In some embodiments, the controller **200** includes a plurality of electrical and electronic components that provide power, operational control, and protection to the components and modules within the controller **200** and/or shovel **10**. For example, the controller **200** includes, among other things, a processing unit **250** (e.g., a microprocessor, a microcontroller, or another suitable programmable device), a memory **255**, input units **260**, and output units **265**. The processing unit **250** includes, among other things, a control unit **270**, an arithmetic logic unit ("ALU") **275**, and a plurality of registers **280** (shown as a group of registers in FIG. **2**), and is implemented using a known computer architecture, such as a modified Harvard architecture, a von Neumann architecture, etc. The processing unit **250**, the memory **255**, the input units **260**, and the output units **265**, as well as the various modules connected to the controller **200** are connected by one or more control and/or data buses (e.g., common bus **285**). The control and/or data buses are shown generally in FIG. **2** for illustrative purposes. The use of one or more control and/or data buses for the interconnection between and communication among the various modules and components would be known to a person skilled in the art in view of the invention described herein. In some embodiments, the controller **200** is implemented partially or entirely on a semiconductor (e.g., a field-programmable gate array ["FPGA"] semiconductor) chip, such as a chip developed through a register transfer level ("RTL") design process.

The memory **255** includes, for example, a program storage area and a data storage area. The program storage area and the data storage area can include combinations of different types of memory, such as read-only memory ("ROM"), random access memory ("RAM") (e.g., dynamic RAM ["DRAM"], synchronous DRAM ["SDRAM"], etc.), electrically erasable programmable read-only memory ("EEPROM"), flash memory, a hard disk, an SD card, or other suitable magnetic, optical, physical, or electronic memory devices. The processing unit **250** is connected to the memory **255** and executes software instructions that are capable of being stored in a RAM of the memory **255** (e.g., during execution), a ROM of the memory **255** (e.g., on a generally permanent basis), or another non-transitory computer readable medium such as another memory or a disc. Software included in the implementation of the shovel **10** can be stored in the memory **255** of the controller **200**. The software includes, for example, firmware, one or more applications, program data, filters, rules, one or more program modules, and other executable instructions. The controller **200** is configured to retrieve from memory and execute, among other things, instructions related to the control processes and methods described herein. In other constructions, the controller **200** includes additional, fewer, or different components. The network communications module **245** is configured to connect to and communicate through a network **290**. The connections between the network communications module **245** and the network **290** are, for example, wired connections, wireless connections, or a combination of wireless and wired connections. Similarly, the connections between the controller **200** and the network **290** or the network communications module **245** are wired connections, wireless connections, or a combination of wireless and wired connections.

The power supply module **235** supplies a nominal AC or DC voltage to the controller **200** or other components or modules of the shovel **10**. The power supply module **235** is powered by, for example, a power source having nominal line voltages between 100V and 240V AC and frequencies of approximately 50-60 Hz. The power supply module **235** is also configured to supply lower voltages to operate circuits and components within the controller **200** or shovel **10**. In other constructions, the controller **200** or other components and modules within the shovel **10** are powered by one or more batteries or battery packs, or another grid-independent power source (e.g., a generator, a solar panel, etc.).

The user interface module **210** is used to control or monitor the power shovel **10**. For example, the user interface module **210** is operably coupled to the controller **200** to control the position of the dipper **70**, the position of the boom **35**, the position of the dipper handle **85**, the transmission unit **100**, etc. The user interface module **210** includes a combination of digital and analog input or output devices required to achieve a desired level of control and monitoring for the shovel **10**. For example, the user interface module **210** includes a display (e.g., a primary display, a secondary display, etc.) and input devices such as touch-screen displays, a plurality of knobs, dials, switches, buttons, etc. The display is, for example, a liquid crystal display ("LCD"), a light-emitting diode ("LED") display, an organic LED ("OLED") display, an electroluminescent display ("ELD"), a surface-conduction electron-emitter display ("SED"), a field emission display ("FED"), a thin-film transistor ("TFT") LCD, etc. The user interface module **210** can also be configured to display conditions or data associated with the power shovel **10** in real-time or substantially real-time. For example, the user interface module **210** is configured to display measured electrical characteristics of the power shovel **10**, the status of the power shovel **10**, the position of the dipper **70**, the position of the dipper handle **85**, etc. In some implementations, the user interface module **210** is controlled in conjunction with the one or more indicators **205** (e.g., LEDs, speakers, etc.) to provide visual or auditory indications of the status or conditions of the power shovel **10**.

FIG. **3** illustrates a more detailed control system **400** for the power shovel **10**. For example, the power shovel **10** includes a primary controller **405**, a network switch **410**, a control cabinet **415**, an auxiliary control cabinet **420**, an operator cab **425**, a first hoist drive module **430**, a second hoist drive module **435**, a crowd drive module **440**, a swing drive module **445**, a hoist field module **450**, a crowd field module **455**, and a swing field module **460**. The various components of the control system **400** are connected by and communicate through, for example, a fiber-optic communication system utilizing one or more network protocols for industrial automation, such as process field bus ("PROFIBUS"), Ethernet, ControlNet, Foundation Fieldbus, INTERBUS, controller-area network ("CAN") bus, etc. The control system **400** can include the components and modules described above with respect to FIG. **2**. For example, the one or more hoist motors and/or drives **215** correspond to first and second hoist drive modules **430** and **435**, the one or more crowd motors and/or drives **220** correspond to the crowd drive module **440**, and the one or more swing motors and/or drives **225** correspond to the swing drive module **445**. The user interface **210** and the indicators **205** can be included in the operator cab **425**, etc. The loadpin strain gauge, the inclinometer **110**, and the gantry pins can provide electrical signals to the primary controller **405**, the controller cabinet **415**, the auxiliary cabinet **420**, etc.

The first hoist drive module **430**, the second hoist drive module **435**, the crowd drive module **440**, and the swing drive module **445** are configured to receive control signals from, for example, the primary controller **405** to control hoisting, crowding, and swinging operations of the shovel **10**. The control signals are associated with drive signals for hoist, crowd, and swing motors **215**, **220**, and **225** of the shovel **10**.

As the drive signals are applied to the motors **215**, **220**, and **225**, the outputs (e.g., electrical and mechanical outputs) of the motors are monitored and fed back to the primary controller **405** (e.g., via the field modules **450-460**). The outputs of the motors include, for example, motor speed, motor torque, motor power, motor current, etc. Based on these and other signals associated with the shovel **10** (e.g., signals from the inclinometer **110**), the primary controller **405** is configured to determine or calculate one or more operational states or positions of the shovel **10** or its components. In some embodiments, the primary controller **405** or the auxiliary controller cabinet **420** determines a dipper position, a dipper handle angle or position, a hoist wrap angle, a hoist motor rotations per minute ("RPM"), a crowd motor RPM, a dipper speed, a dipper acceleration, etc.

Optimizing the performance of the shovel **10** through a digging operation can improve the payload capacity of the shovel **10** without, for example, increasing structural loading and fatigue on the shovel **10**, reducing the operational life of the shovel **10**, or increasing the cost of the shovel **10**. As an illustrative example, the controller **200** or the primary controller **405** are configured to implement optimized digging control ("ODC") based on a position of the dipper **70**, the dipper handle **85**, etc. For example, when implementing ODC, the controller **200** is configured to determine the position of the dipper **70** in space or with respect to other components of the shovel **10**, and dynamically control hoist forces based on the determined position of the dipper **70**. The dynamic control of the hoist forces includes actively controlling a level of hoist bail pull with respect to the position of the dipper **70** as the shovel **10** executes a digging operation. ODC limits the shovel's digging capability at certain areas within the digging envelope **120** (see FIG. **1**), but increases the overall load capacity of the shovel **10** with respect to the complete digging operation. For example, ODC is configured to increase hoist bail pull in certain areas of the digging envelope **120**, as opposed to limiting hoist bail pull at full extension. In some embodiments, ODC increases hoist bail pull low in the digging envelope **120** and gradually decreases the hoist bail pull higher in the digging envelope **120**. As a result of the increase in hoist bail pull, fill factors for the shovel **10** are increased and the digging cycle time of the shovel **10** is decreased (e.g., the dipper **70** is pulled out of the bank sooner). In some embodiments, ODC is also configured to control the hoist bail pull for extended handle reaches to allow the use of a longer dipper handle for extended dumping reaches (e.g., toward a pile, toward a truck, etc.). For example, by enabling the use of a longer dipper handle, the spotting range of a truck can be extended to simplify the loading of large trucks. In some embodiments, ODC utilizes cycle time decomposition to determine whether the shovel **10** has completed a digging operation and allow for extended crowd reach by further limiting hoist bail pull (e.g., below a standard operating value).

An illustrative example of a process for controlling a level of hoist bail pull with respect to a position of the dipper **70** is shown in and described with respect to FIG. **4**. Specifically, FIG. **4** illustrates a process **500** having corresponding computer readable instructions that can be executed by, for example, the controller **200** or the primary controller **405** for controlling a hoist bail pull level based on a position of the dipper **70**. At step **505**, the position of the dipper **70** is determined. The dipper position is determined based on, for example, the use of one or more resolvers, inclinometers, hoist rope wrap angles, etc. In some embodiments, a position (e.g., a radial position) of the dipper handle **85** is determined using one or more resolvers and is used alone or in combination with the dipper position to control the level of hoist bail pull. After the position of the dipper **70** has been determined, the position of the dipper **70** is compared to REGION-A **125** (see FIG. **1**) (step **510**). If, at step **510**, the position of the dipper **70** is within REGION-A, the hoist bail pull is set to a first hoist limit ("HL1") (step **515**). The process **500** then returns to step **505** and section A where the position of the dipper **70** is again determined. If, at step **510**, the position of the dipper **70** is not within REGION-A, the process **500** proceeds to step **520**. At step **520**, if the position of the dipper **70** is within REGION-B **130** (see FIG. **1**), the hoist bail pull is set to a second hoist limit ("HL2") (step **525**). The process **500** then returns to step **505** and section A where the position of the dipper **70** is again determined. If, at step **520**, the position of the dipper **70** is not within REGION-B, the process **500** proceeds to step **530**. At step **530**, if the position of the dipper **70** is within REGION-C **135** (see FIG. **1**), the hoist bail pull is set to a third hoist limit ("HL3") (step **535**). The process **500** then returns to step **505** and section A where the position of the dipper **70** is again determined. If, at step **530**, the position of the dipper **70** is not within REGION-C, the process **500** proceeds to step **540** where the hoist bail pull is set to a fourth hoist limit ("HL4") (step **540**). The process **500** then returns to step **505** and section A where the position of the dipper **70** is again determined. The limits of REGION-A **125**, REGION-B **130**, and REGION-C **135** can be set, established, or determined based on, for example, the type of industrial machine, the type or model of shovel, etc.

As described in the illustrative example above, the digging envelope **120** of the shovel **10**'s digging operation is divided into three sections that correspond to REGION-A **125**, REGION-B **130**, and REGION-C **135**. REGION-A **125** corresponds to the lowest or inner portion of the digging envelope **120** of the digging operation and has the largest relative hoist bail pull setting with respect to the remaining regions. REGION-B **130** is adjacent to REGION-A **125** in the digging envelope **120** and has a lower hoist bail pull setting than REGION-A **125**, but a larger hoist bail pull setting that REGION-C **135**. REGION-C **135** corresponds to the highest or outer portion of the digging envelope **120** of the digging operation and has the lowest hoist bail pull setting with respect to the other regions.

The hoist bail pull limits HL1, HL2, HL3, and HL4 corresponding to the regions of the digging envelope **120** can be set to a variety of values or levels for the hoist drive modules **430** and **435**. As an illustrative example, HL1, HL2, HL3, and HL4 decrease from a level that exceeds a standard hoist bail pull (e.g., hoist bail pull≈120% of the standard hoist bail pull) to the standard hoist bail pull that corresponds to a normal maximum operational value (e.g., a rated value) for the hoist bail pull (i.e., ≈100%). In one embodiment, HL1≈120%, HL2≈110%, HL3≈100%, and HL4≈100%. In some embodiments, HL4 can be set to a value below approximately 100% hoist bail pull to enable the use of a longer dipper handle with the shovel **10**. In other embodiments, HL1, HL2, HL3 and HL4 can take on different values. However, regardless of the specific values or ranges of values that HL1, HL2, HL3, and HL4 take on, the relationship between the relative magnitudes of the limits remain the same (e.g., HL1>≈HL2>≈HL3>≈HL4). In some embodiments, each of the hoist bail pull limits HL1, HL2, HL3, and HL4 produce approximately the same forward tipping moment and CG excursion on the shovel **10**. In some embodiments, the hoist bail pull can also be set to greater than approximately 120% of the normal operation limit for hoist bail pull. In such embodiments, the hoist bail pull is limited to, for example, operational characteristics of the one or more hoist motors **215** (e.g., some motors can allow for greater excess hoist bail pull than others). As such, the hoist bail pull is capable of being set to a value of between approximately 75% and 150% of the normal operational limit based on the characteristics of the one or more hoist motors **215**.

By increasing the hoist bail pull low in the digging envelope, the dipper **70** generates a greater payload early in the digging operation and increases the cutting force applied to, and the speed at which the dipper **70** cuts through, the bank early in the digging operation. Gantry pin load and other structural loading also increases with increased payload. However, as a result of the hoist bail pull being increased low in the digging envelope and reduced to approximately the standard operational value higher in the digging envelope, the tipping moment resulting from the digging operation produces a CG excursion of the shovel **10** that is no greater than (i.e., less than or approximately equal to) the CG excursion that would be experienced by the shovel **10** had the hoist bail pull remained at the standard operational value throughout the digging operation.

In some embodiments, the digging envelope **120** is divided into additional (e.g., more than three) or fewer (i.e., two) sections for which the level of hoist bail pull is modified. In embodiments of the invention in which the digging envelope **120** is divided into more than three sections, the number of sections that can be used can be substantially larger than three (e.g., several hundred). For example, the greater the number of sections that the digging envelope **120** is divided into, the more precise and gradual the modification of the hoist bail pull setting becomes. In some embodiments, the number of sections for which the digging envelope **120** is divided is based on the level of precision for which the hoist bail pull can be controlled. In other embodiments, the digging envelope is not divided into sections. Instead, a function is used to calculate a hoist bail pull setting based on the determined position of the dipper **70** or dipper handle **85**. In such embodiments, the modifications that can be made to the hoist bail pull setting are substantially continuous. In other embodiments, a look-up table ("LUT") can be used to look up a hoist bail pull setting based on a determined or calculated position of the dipper **70** or dipper handle **85**.

FIGS. **5-8** illustrate hoist bail pull vs. bail speed curves for an embodiment of the invention that includes three regions for which the hoist bail pull is set or modified. FIG. **5** illustrates curves **605**, **610**, and **615** for each of REGION-A **125**, REGION-B **130**, and REGION-C **135**, respectively, described above. FIGS. **6-8** illustrate the individual curves **605**, **610**, and **615** corresponding to each of REGION-A **125**, REGION-B **130**, and REGION-C **135**, respectively. As illustrated in FIGS. **5-8**, the largest relative hoist bail pull is provided in REGION-A **125**. The level of hoist bail pull is set to a lower level for REGION-B **130** and REGION-C **135**. For bail speeds that are below approximately 175 feet per minute ("FPM"), the intervals for hoist bail pull settings are substantially constant (i.e., linear). As the bail speed increases, the levels of hoist bail pull in each of the regions is gradually reduced (e.g., as a function of maximum horsepower ["HP"]) until a speed is achieved for which the levels of hoist bail pull in each of the regions is approximately the same. Such a condition is uncommon due to the resistance the dipper **70** encounters when digging a bank. In general, the resistance provided by the bank during a digging operation often prevents the bail speed from increasing substantially beyond the linear portion of the illustrated torque-speed curves.

Although the torque speed curves provided in FIGS. **5-8** are shown with a range of hoist bail pull settings between zero and 600 lbs (×1000), the actual hoist bail pull settings can vary depending on, for example, the type, size, or model of shovel, hoist motor HP, etc. For example, in some embodiments, the torque-speed curves range from zero to 800 lbs (×1000), zero to 1000 lbs (×1000), etc. The levels of hoist bail pull for each of the regions can also be set based on, among other things, digging conditions, shovel model, shovel type, shovel age, dipper type, etc. For example, in one embodiment, the hoist bail pull in REGION-C **135** is set to 500 lbs (×1000), the hoist bail pull in REGION-B **130** is set to 550 lbs (×1000), and the hoist bail pull in REGION-A **125** is set to 600 lbs (×1000). However, such levels of hoist bail pull are exemplary and can vary from one embodiment of the invention to another.

Thus, the invention provides, among other things, systems, methods, devices, and computer readable media for controlling a digging operation of an industrial machine. Various features and advantages of the invention are set forth in the following claims.

What is claimed is:

1. A method of controlling a digging operation of an industrial machine, the industrial machine including a component and a hoist drive, the method comprising:
- determining a first position of the component during the digging operation;
- determining, using a processor, a first hoist force setting based on the first position of the component;
- setting, using the processor, a first level of hoist force for the hoist drive to the first hoist force setting;
- determining a second position of the component during the digging operation;
- determining, using the processor, a second hoist force setting based on the second position of the component; and
- setting, using the processor, a second level of hoist force for the hoist drive to the second hoist force setting,
- wherein the first level of hoist force is greater than the second level of hoist force.

2. The method of claim **1**, wherein the first position of the component corresponds to an earlier position in the digging operation than the second position of the component.

3. The method of claim **1**, wherein the first level of hoist force exceeds a normal operating value for hoist force.

4. The method of claim **1**, wherein the industrial machine is a rope shovel.

5. The method of claim **1**, wherein the first hoist force setting is further determined based on a relationship between component position and hoist force, and wherein the relationship corresponds to a function for calculating a hoist force based on component position.

6. The method of claim **1**, further comprising monitoring a center-of-gravity ("CG") excursion of the industrial machine during the digging operation.

7. The method of claim **1**, wherein the component is a dipper.

8. The method of claim **1**, wherein a tipping moment of the industrial machine at the first position is approximately equal to the tipping moment of the industrial machine at the second position.

9. The method of claim **1**, wherein the industrial machine is a hydraulic machine.

10. The method of claim **1**, wherein the hoist drive is configured to provide a first control signal to a hoist actuator based on the first level of hoist force and a second control signal to the hoist actuator based on the second level of hoist force.

11. The method of claim **10**, wherein the hoist drive is a hoist motor drive.

12. The method of claim 10, wherein the hoist actuator generates a hoist force that is provided to the component, the generated hoist force being limited to one of the first level of hoist force and the second level of hoist force.

13. The method of claim 12, wherein the hoist actuator is a hoist motor and the hoist force is a hoist motor torque generated by the hoist motor.

14. The method of claim 13, wherein the hoist motor torque drives a winch drum to pay out or pull in a hoist rope to lower or raise the component.

15. An industrial machine comprising:

a dipper;

a hoist drive configured to generate a signal related to a force to be applied to the dipper as the dipper is moved through a digging operation; and

a controller connected to the hoist drive, the controller including a processor and executable instructions stored in a computer readable medium, the controller configured to retrieve and execute the instructions to

determine a first position of the dipper associated with the digging operation,

determine a first hoist setting based the first position,

set a first level of hoist for the hoist drive to the first hoist setting,

determine a second position of the dipper associated with the digging operation,

determine a second hoist setting based on the second position, and

set a second level of hoist for the hoist drive to the second hoist setting,

wherein the first level of hoist is different than the second level of hoist.

16. The industrial machine of claim 15, wherein the industrial machine is a rope shovel.

17. The industrial machine of claim 15, wherein the second level of hoist corresponds to a normal operating value for hoist.

18. The industrial machine of claim 17, wherein a tipping moment of the industrial machine at the first position is approximately equal to the tipping moment of the industrial machine at the second position, and wherein the tipping moment is less than or approximately equal to a tipping moment of a second industrial machine for which the first level of hoist and the second level of hoist are each set to the normal operating value for hoist.

19. The industrial machine of claim 18, wherein the controller is further configured to monitor the tipping moment of the industrial machine during the digging operation.

20. The industrial machine of claim 15, wherein the hoist drive is configured to provide a first control signal to a hoist actuator based on the first level of hoist and a second control signal to the hoist actuator based on the second level of hoist.

21. The industrial machine of claim 20, wherein the hoist drive is a hoist motor drive.

22. The industrial machine of claim 20, wherein the hoist actuator generates the force to be applied to the dipper, the generated force being limited to one of the first level of hoist and the second level of hoist.

23. The industrial machine of claim 22, wherein the hoist actuator is a hoist motor and the force is a hoist motor torque generated by the hoist motor.

24. The industrial machine of claim 23, wherein the hoist motor torque drives a winch drum to pay out or pull in a hoist rope to lower or raise the dipper.

25. A method of controlling the operation of an industrial machine, the industrial machine including a component, the method comprising:

determining, using a processor, a position of the component of the industrial machine during a digging operation of the industrial machine;

determining, using the processor, a hoist force setting based on the position of the component; and

setting, using the processor, a level of hoist force to the hoist force setting,

wherein the level of hoist force during the digging operation is reduced based on the position of the component in relation to the industrial machine, the level of hoist force having a greater value when the component is at a first position during the digging operation than when the component is at a second position during the digging operation.

26. The method of claim 25, wherein the component is a dipper handle.

27. The method of claim 25, wherein the component is a dipper.

28. The method of claim 27, wherein the hoist force setting is further determined based on a relationship between dipper position and hoist force, and wherein the relationship corresponds to a function for calculating a hoist force based on dipper position.

29. The method of claim 28, wherein the function reduces the level of hoist force during the digging operation.

30. The method of claim 25, wherein the digging operation includes a digging envelope.

31. The method of claim 30, wherein the digging envelope is divided into two or more sections corresponding to different levels of hoist force.

32. The method of claim 25, further comprising monitoring a tipping moment of the industrial machine during the digging operation.

33. The method of claim 25, wherein the level of hoist force early in the digging operation exceeds a normal operating value for hoist force.

34. The method of claim 25, wherein the industrial machine is a rope shovel.

35. The method of claim 34, wherein the position of the component is determined based on a hoist rope wrap angle.

36. The method of claim 25, wherein the first position is closer to the industrial machine than the second position.

37. The method of claim 36, wherein the first position corresponds to an earlier position in the digging operation than the second position.

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